D mesons in matter and the in-medium properties of charmonium

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Abstract

We study the changes in the partial decay widths of excited charmonium states into $D\bar{D}$, when the D meson mass decreases in nuclear matter, taking the internal structure of the hadrons into account. Calculations within the 3P0 model for $\psi(3686)$ and $\psi(3770)$ imply that naive estimates of the in-medium widths based only on phase space are grossly exaggerated. Due to nodes in the wave functions, these states may even become narrow at high densities, if the D meson mass is decreased by about 200 MeV. For the χ states, we generally expect stronger modifications of the widths. The relevance of the χ widths for J/ψ suppression in heavy ion collision is discussed. These phenomena could be explored in experiments at the future accelerator facility at GSI.

Key words: D mesons, Charmonium, QCD in nuclear physics, nuclear matter
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1 Introduction

The study of hadrons containing heavy quarks is an important tool for unraveling the properties of the non-perturbative QCD vacuum. In particular, in mesons consisting of one heavy and one light quark, such as the D meson, the heavy quark acts as an almost static source for the light quark, which in turn probes the QCD vacuum. This is the basic constituent quark picture of heavy-light meson systems within the formulation based on heavy quark symmetry [1]. Therefore, changes in the vacuum condensates, e.g., at finite temperature and density, are expected to affect the light quark and consequently also to modify the in-medium properties of the D meson. This is explicitly borne out in the model calculations based on QCD sum rule analysis [2,3] and the Quark Meson coupling model [4], both of which show a reduction of the D meson mass of about 50 MeV at nuclear matter density. Lattice gauge theory results for the heavy quark potential at finite temperature, suggests a similar drop of the D meson mass at finite temperature [5].

The reduction of the D-meson mass obviously has important phenomenological consequences, ranging from the possible existence of charmed mesic nuclei [4] to enhanced subthreshold production of open charm in $\bar{p}A$ reactions [6]. Moreover, a reduction of the D-meson mass in matter has also direct consequences for the production of open charm [7] and the suppression of J/ψ-mesons [8] in relativistic heavy ion collisions. Such phenomena could be explored in experiments e.g. at the future accelerator facility at GSI [9].

The decrease of the D-meson mass in matter is by and large due to the restoration of chiral symmetry in the nuclear medium. This is demonstrated by QCD sum rule calculations of the D meson mass in vacuum [10] and in matter [2,3]. In the D-meson sum rules, the leading term is dominated by chiral symmetry breaking operators. This is contrary to heavy quarkonia, such as J/ψ and $\psi(3686)$, where the constituent quark and antiquark probe only the gluonic condensates. Consequently, such states are expected to experience only a relatively small mass shift in medium [11–16]. This implies that, with increasing density, the $D\bar{D}$ threshold [2,5,17,18] will cross the energy of some of the excited charmonium states. Consequently, the reduction of the $D\bar{D}$ threshold in matter may be reflected in the dilepton spectrum of $\bar{p}A$ or AA reactions as an increased width of the peaks corresponding to the $\psi(3686)$ state. Furthermore, since more than 40% of the J/ψ produced in heavy ion collision emanate from the $\psi(3686)$ and χ states [19], such crossings will induce a stepwise suppression of J/ψ signal due to the successive melting of excited charmonium states at finite density and temperature [2,5,17,18].

In this letter, we point out that the level crossing between the charmonium and the $D\bar{D}$ threshold does not result in an immediate dissolving of the charmonium states, as found in naive calculations, where the participating mesons are effectively treated as point particles. When the internal structure is taken into account, the effective coupling to the $D\bar{D}$ final state depends strongly on the Q-value, and consequently on the momentum carried by D meson in the charmonium rest frame. The overlap of the D mesons with the wavefunction of the initial heavy quarks of the charmonium depends strongly on the relative momentum of the D mesons in the final state. In other words, the effective $\psi D\bar{D}$ coupling constant is sensitive to the wave functions and the momenta of the particles involved in the decay. This mechanism provides a viable interpretation [20] of the experimentally observed branching ratios for the decay of the $\psi(4040)$ into $D\bar{D}, D\bar{D}^*, D^*\bar{D}^*$. There are strong deviations from predictions based on naive quark spin counting. It was shown that the effective coupling between $\psi(4040)$ and the D mesons varies rapidly with the relative momentum in the final state. The matrix elements may even vanish at certain momenta, corresponding to nodes in the wave function [20]. This mechanism was confirmed also in a more sophisticated potential model for the heavy quarkonium [21].

As we will show, a similar mechanism is active also in the decay of $\psi(3686)$, $\psi(3770)$, $\chi_{c0}(3417)$ and $\chi_{c2}(3556)$ into $D\bar{D}$ as the mass of the D meson decreases. Due to the nodes in the radial ($\psi(3686)$) and orbital ($\psi(3770)$) wave function, the partial decay widths first increase and then decrease as the mass of the D meson is reduced. In particular we find that, for a mass shift of $200 - 250$ MeV, the branching ratio into the $D\bar{D}$ channel vanishes and then increases again when the D mass is reduced further. The resulting widths are much smaller than those obtained in the naive picture, where the width is enhanced due to the increase in phase space, while the coupling constant is kept fixed.

For the χ mesons the picture is somewhat different. The partial width of the $\chi_{c0}(3417)$, increases very rapidly as the $D\bar{D}$ channel opens up, and then approaches zero as the mass of the D meson is decreased even further. On the other hand, for the $\chi_{c2}(3556)$ the partial decay width increases slowly and monotonically, because there is no node in the wave function.

2 Charmonium states

We use the harmonic oscillator potential to model the bound state wave functions and the 3P0 model to describe the charmonium decays. In this exploratory calculation our aim is to determine the in-medium properties of the excited charmonium states on a semi-quantitative level. Our main result, the medium dependence of the effective coupling constants, is due mainly to the node structure of the wave functions and does not depend strongly on the details of the model. Hence, a more sophisticated calculation based on a refined potential will not change the main conclusions of our work. In the harmonic oscillator potential model, the wave function of a heavy quarkonium state is of the form,

$$\phi_{N,l} = \text{Normalization} \times Y_l^m(\theta,\phi)(\beta^2 r^2)^{\frac{1}{2}l} e^{-\frac{1}{2}\beta^2 r^2} L_{N-1}^{l+\frac{1}{2}}(\beta^2 r^2) \quad (1)$$

where $\beta^2 = M\omega/\hbar$ characterizes the strength of the harmonic potential, $M = \frac{1}{2}m_c$ is the reduced mass of the charm quark anti-quark system, and $L_p^k(z)$ is a Laguerre Polynomial. The energy eigenvalues are

Table 1
Charmonium states in the harmonic oscillator model.

Charmonium	$N\,^{2S+1}L_J$	HO energy	$\Gamma(e^+e^-)$ (KeV)	$\Gamma(Tot)$ (MeV)	$g_{\psi DD}$
$J/\psi(3097)$	$1\,^3S_1$	$\frac{3}{2}\hbar\omega$	5.26	0.087	7.8
$\psi(3686)$	$2\,^3S_1$	$(\frac{3}{2}+2)\hbar\omega$	2.14	0.277	
$\psi(3770)$	$1\,^3D_1$	$(\frac{3}{2}+2)\hbar\omega$	0.28	23.6	15.4
$\chi_{c0}(3417)$	$1\,^3P_0$	$(\frac{3}{2}+1)\hbar\omega$		14	
$\chi_{c1}(3510)$	$1\,^3P_1$	$(\frac{3}{2}+1)\hbar\omega$		0.88	
$\chi_{c2}(3556)$	$1\,^3P_2$	$(\frac{3}{2}+1)\hbar\omega$		2	

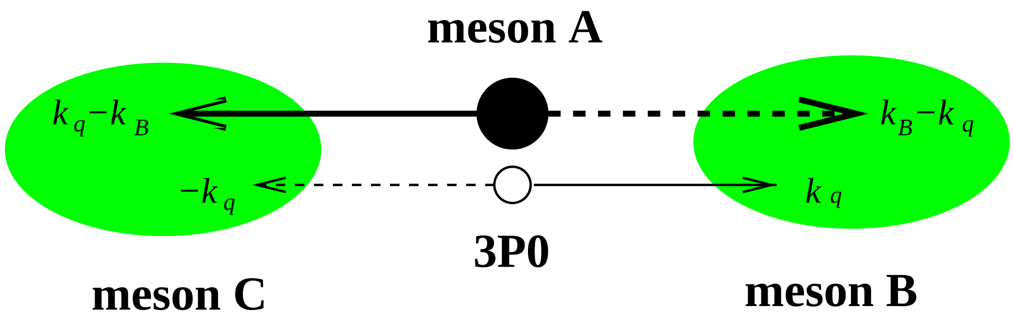

Fig. 1. Diagrammatic representation of meson A decaying into mesons B and C by creating a 3P0 quark anti-quark pair.

$$E_n = \hbar\omega(n + \frac{1}{2}), \qquad n = 2k + l + 1 = 2(N-1) + l + 1, \tag{2}$$

where, N is the number or nodes in the radial direction, including one at infinity. In table I, we summarize the quark-model assignments of quantum numbers and other relevant information on the lowest lying charmonium states. For the $\psi(3770)$, the coupling constant $g_{\psi DD}$ is determined by fitting its width using $\Gamma_{Tot} = \Gamma_{\psi \to DD} = (g^2_{\psi DD}/24\pi)((m^2_\psi - 4m^2_D)^{3/2}/m^2_\psi)$. For the $J/\psi(3097)$, which is far below the $D\bar{D}$ threshold, we use vector meson dominance for the electromagnetic current of the D-meson, assuming that the form factor is dominated by the J/ψ at small q^2. In vacuum the $D\bar{D}$ threshold is located at 3.74 GeV.

3 The 3P0 model

We compute the decay of the charmonium states into $D\bar{D}$ mesons using the 3P0 model [22]. In this model, the decay of a meson A into mesons B and C involves the following invariant matrix element

$$M_{A\to BC} = \langle A|\gamma\left[\bar{q}_s q_s\right]^{3P_0}|BC\rangle, \tag{3}$$

where γ is a coupling strength, which characterizes the probability for creating a quark anti-quark pair in the $3P_0$ state. In fig. 1 we show a diagrammatic representation in the rest frame of the meson A consisting of a heavy quark anti-quark pair with momenta $k_q - k_B$ and $k_B - k_q$. The decay products are the mesons B and C with total momenta k_B and $-k_B$ respectively. The meson B is composed of a heavy anti-quark (momentum $k_B - k_q$) emanating from the parent meson A and a quark (momentum k_q) from the 3P0 pair. Now, since the decaying quarks has to form the physical meson, the matrix element will involve the following overlap integral,

$$\begin{aligned} M_{A\to BC} \propto \int d^3k_q \phi_A(2k_q - 2k_B)\phi_B(2k_q - k_B)\phi_C(2k_q - k_B) \\ \times\left[\bar{u}_{k_q,s} v_{-k_q,s}\right]^{3P_0} \end{aligned} \tag{4}$$

where the mesonic wave functions ϕ are the Fourier transforms of the spatial wave functions in Eq. (1). The momentum space wave functions are polynomial functions in the relative momentum multiplied by gaussians. Finally, $\left[\bar{u}_{k_q,s} v_{-k_q,s}\right]^{3P_0} \propto k_q Y_1^m(k_q)$ is the wave function of the produced $\bar{q}q$ pair.

The overlap integral in eq.(4), is a function of the meson momentum k_B. When there are nodes in one of the wave functions ϕ, the integral can vanish for certain values of k_B. This is seen by combining the three gaussians in eq. (4) into one. To this end one makes a change of variables

$$k'_q = k_q - \frac{1+r^2}{1+2r^2}k_B, \tag{5}$$

where $r = \frac{\delta}{\beta}$, δ is the strength of the HO potential of the parent meson A and β is that of the emitted mesons B and C. We introduce two independent parameters β and δ to allow for different sizes of the wave function for the initial meson and the outgoing mesons. Now, if one or more of the mesons involved is in an excited state, the polynomial in the corresponding wave function ϕ is, after the change of variables (5), a polynomial in k_B and k'_q. Consequently, the matrix element (4) is proportional to a polynomial in k_B, which may vanish for certain values of k_B.

For the case of interest, where the charmonium decays into two pseudoscalar mesons $D\bar{D}$, the relevant formulae in the 3P0 model can be found in ref. [23] for $\beta = \delta$. Here, we re-derive the formula in 3P0 model, allowing for $\beta \neq \delta$. The invariant matrix element for the decay $A \to B + C$ is given by,

$$M_{LS} = \frac{\gamma}{\pi^{1/4}\beta^{1/2}} \mathcal{P}_{LS}(x,r) e^{-\frac{x^2}{4(1+2r^2)}} \times \frac{1}{2}[I(d_1) + I(d_2)]. \quad (6)$$

In our case, the flavor factors $\frac{1}{2}[I(d_1) + I(d_2)] = \frac{1}{2}$. Furthermore,

$$x = \frac{1}{\beta} \times \sqrt{m_A^2/4 - m_B^2}\,, \quad (7)$$

which is the scaled momentum carried by the decaying mesons in the rest frame of the parent meson A. The decay rate is then given by

$$\Gamma(A \to B + C) = 2\pi \frac{p_B E_B E_C}{M_A} \sum_{LS} |M_{LS}|^2\,. \quad (8)$$

We now present the resulting decay rates for the different charmonium states. The quark-model assignments of these states are given in Table 1. For $r = 1$ ($\beta = \delta$), our results reduce to those given of Barnes *et al.* [23].

(1) $\chi(3417)$

$$\mathcal{P}_{00}^{(1\ ^3P_0 \to ^1S_0 + ^1S_0)} = \sqrt{\frac{3}{2}} \times 2^5 \Big(\frac{r}{1+2r^2} \Big)^{5/2} \Big(1 - \frac{(1+r^2)}{3(1+2r^2)} x^2 \Big), \quad (9)$$

$$\begin{aligned}\Gamma(\chi(3417) \to D + \bar{D}) = & \frac{\pi^{1/2} E_D^2}{M_{\psi(3417)}} \gamma^2 2^9 3 \Big(\frac{r}{1+2r^2} \Big)^5 x \\ & \times \Big(1 - \frac{(1+r^2)}{3(1+2r^2)} x^2 \Big)^2 e^{-\frac{x^2}{2(1+2r^2)}}. \end{aligned} \quad (10)$$

(2) $\chi(3556)$

$$\mathcal{P}_{20}^{(1\ ^3P_2 \to ^1S_0 + ^1S_0)} = \frac{1}{\sqrt{15}} \times \frac{r^{5/2} 2^5 (1+r^2)}{(1+2r^2)^{7/2}} x^2, \quad (11)$$

$$\Gamma(\chi(3556) \to D + \bar{D}) = \frac{\pi^{1/2} E_D^2}{M_{\psi(3556)}} \gamma^2 \frac{2^{10}}{15} \frac{r^5 (1+r^2)^2}{(1+2r^2)^7} x^5 e^{-\frac{x^2}{2(1+2r^2)}}. \quad (12)$$

(3) $\psi(3686)$

$$\begin{aligned}\mathcal{P}_{10}^{(2\ ^3S_1 \to ^1S_0 + ^1S_0)} = & \frac{2^{7/2}(1-3r^2)(3+2r^2)}{3(1+2r^2)^{7/2}} x \\ & \Big(1 + \frac{2r^2(1+r^2)}{(1+2r^2)(3+2r^2)(1-3r^2)} x^2 \Big), \end{aligned} \quad (13)$$

$$\Gamma(\psi(3686) \to D + \bar{D}) = \frac{\pi^{1/2} E_D^2}{M_{\psi(3686)}} \gamma^2 \frac{2^7}{3^2} \frac{(3+2r^2)^2(1-3r^2)^2}{(1+2r^2)^7} x^3$$
$$\times \left(1 + \frac{2r^2(1+r^2)}{(1+2r^2)(3+2r^2)(1-3r^2)} x^2\right)^2 e^{-\frac{x^2}{2(1+2r^2)}}. \quad (14)$$

(4) $\psi(3770)$

$$\mathcal{P}_{10}^{(1\ ^3D_1 \to ^1S_0 + ^1S_0)} = -\frac{2^5\sqrt{10}}{3} \left(\frac{r}{1+2r^2}\right)^{7/2} x \left(1 - \frac{1+r^2}{5(1+2r^2)} x^2\right), \quad (15)$$

$$\Gamma(\psi(3770) \to D + \bar{D}) = \frac{\pi^{1/2} E_D^2}{M_{\psi(3770)}} \gamma^2 \frac{2^{11}5}{3^2} \left(\frac{r}{1+2r^2}\right)^7 x^3$$
$$\times \left(1 - \frac{1+r^2}{5(1+2r^2)} x^2\right)^2 e^{-\frac{x^2}{2(1+2r^2)}}. \quad (16)$$

Note that in each case, x is defined by eq.(7) with m_A the mass of the corresponding charmonium state and $m_B = m_D$. The zero in eq.(14) is due to the nodes in the radial wave function, whereas those in eq. (10) and eq. (16) results from the orbital part. Nevertheless, for $r = 1$, the two widths in eq.(14) and eq.(16) have the same functional form.

Our model has three parameters, namely, β, $r = \delta/\beta$ and γ:

- β determines the size of the harmonic oscillator potential of the D mesons, while δ is the corresponding parameter for charmonium. We fix β and the ratio r by fitting the partial decay width of $\psi(4040)$ to DD, DD^* and D^*D^* to the experimental ratios of 1:20:640, as has been done in ref. [20] for $r = 1$. The formulas of ref. [20] can be generalized to $r \neq 1$ by the following replacement,

$$\frac{35}{4 \cdot 3^3}\left(1 - \frac{4}{15}x^2 + \frac{4}{315}x^4\right) \to \left(\frac{15}{8}\frac{1+r^2}{1+2r^2} - \frac{5r^2(4+r^2)}{(1+2r^2)^3}\right.$$
$$\left. + \frac{r^2(5-9r^2-10r^4)}{2(1+2r^2)^4}x^2 + \frac{r^4(1+r^2)}{2(1+2r^2)^5}x^4\right) \quad (17)$$

  The fit yields,

$$\beta = 0.3 \text{ GeV}, \quad \text{and} \quad r = 1.04\,. \quad (18)$$

  The resulting oscillator parameter β is close to the value obtained in ref. [20] ($\beta = 0.31$ GeV) and the ratio r is close to unity. The implied difference in size of the D meson and charmonium is very small and, in view of the simplicity of the model, presumably insignificant. Within the harmonic oscillator model, one can also relate β to the mass splitting between the charmonium states if one assumes an effective charm quark mass m_c. In this

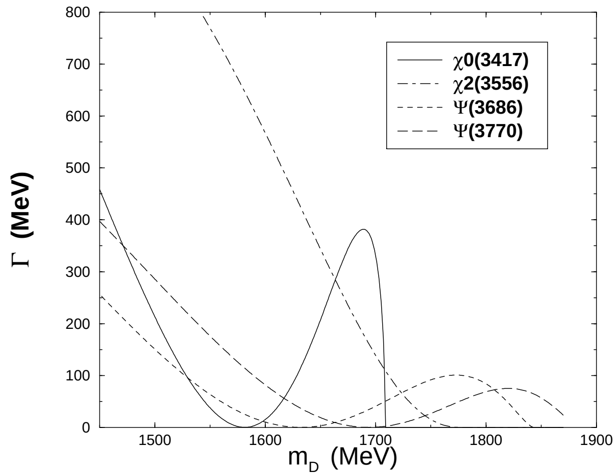

Fig. 2. Partial decay width of charmonium decaying into $D\bar{D}$, as a function of the D meson mass.

case, for $m_c = 1.5$ GeV, we find $\beta \sim 0.43$ GeV. However, since we are interested in the partial decay widths of charmonium states, we will choose the value given in eq.(18).

- γ determines the strength of the 3P0 vertex. This parameter may be determined by fitting the $\Gamma(\psi(3770) \to D\bar{D})$, which implies $\gamma = 0.281$.

These values for the parameters are qualitatively consistent with those obtained from a best fit to the decays of excited states of light mesons [23], $\beta = 0.36$ GeV and $\gamma = 0.4$.

In fig. 2 we show the dependence of the partial widths for the decay into the $D\bar{D}$ channel on the D meson mass in medium. For the $J^{PC} = 1^{--}$ states, we note that when the D-meson mass is reduced, $\Gamma_{D\bar{D}}(\psi(3770))$ and $\Gamma_{D\bar{D}}(\psi(3686))$ first grow to about 90 MeV for a mass shift of about 50 MeV. Due to the nodal structure of the wave function, a further reduction of the D-meson mass leads to a strong decrease of the partial width, which then vanishes for a mass shift of about 200 MeV and 250 MeV, respectively. In both cases, the increase of the width beyond this point is slow, so that even when the D meson mass is reduced by 400 MeV, the widths remain below 350 MeV. In fig. 3, we illustrate the important role of the internal structure of the mesons by comparing the in-medium width of the $\psi(3770)$ (eq.(16)) with the naive estimate obtained by treating the mesons as point particles

$$\Gamma^{\star}_{D\bar{D}}(\psi(3770)) = \frac{g^2_{\psi DD}}{24\pi}\frac{(m_\psi^2 - 4m_D^2)^{3/2}}{m_\psi^2}. \qquad (19)$$

Here the coupling constant is kept fixed at its vacuum value $g_{\psi DD} = 15.4$. Consequently, $\Gamma^{\star}_{D\bar{D}}(\psi(3770))$ grows rapidly with dropping D-meson mass, due to the strong increase in available phase space. Clearly, the width of the $\psi(3770)$

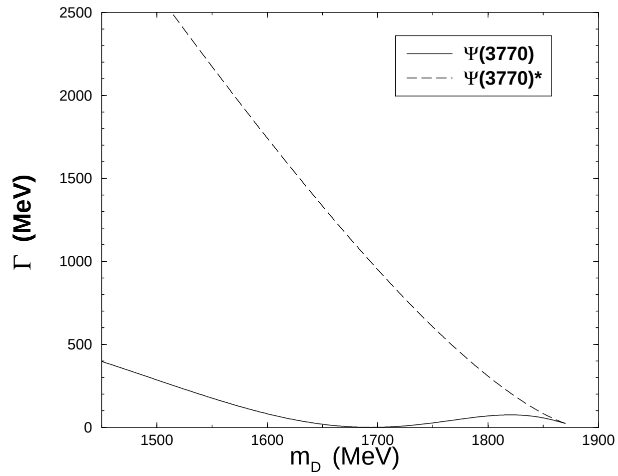

Fig. 3. The solid line is the partial decay width $\Gamma(\psi(3770) \rightarrow D + \bar{D})$ from 3P0 model. The dashed line is assuming a constant coupling normalized to give the same leading behaviour at the threshold point.

in matter is strongly overestimated in the naive calculation, where the internal meson structure is ignored. Consequently, the expectation that the ψ states would melt instantly as the $D\bar{D}$ channel opens up is not well founded.

As shown in fig. 2, the situation for the χ states is somewhat different. The width of the lightest χ meson , the χ_{c0}, increases very rapidly as the decay into the $D\bar{D}$ channel becomes possible. Again, a node in the wave function leads to a zero in the width as the D-meson mass is decreased further. The sudden increase at threshold is due to the fact that in $J^{\pi} = 0^{+}$, the $D\bar{D}$ pair is in an s-wave state. This implies, that $\chi_{c0}(3417)$ will dissolve, when the $D\bar{D}$ channel opens up. However, this will probably have only little impact on J/ψ suppression in heavy ion collisions, since the feeding of J/ψ's from the decay of the $\chi_{c0}(3417)$ is expected to be negligible [19].

On the other hand, the $D\bar{D}$ width of the $\chi_{c2}(3556)$ is suppressed at first, because for $J^{\pi} = 2^{+}$ the D mesons are in an $l = 2$ state. As the D-meson mass is decreased further, this partial width increases monotonically, because the wave function of this state has no nodes. Thus, for large mass shifts, its width is much larger than for the other charmonium states. This behavior could have an important effect on J/ψ suppression in heavy ion collision, since at sufficiently high densities, the produced $\chi_{c2}(3556)$ mesons will melt instantly and not contribute to the production of J/ψ's in heavy ion collision. This would eliminate more than 10% of the expected J/ψ yield [19].

4 Conclusion

We have shown that the internal structure of the mesons play a crucial role in calculations of the in-medium widths of charmonium states. In particular, we find that the dropping of the D meson mass in nuclear matter does not lead to the extreme increase of the decay width of charmonium states, expected from naive phase space arguments. In fact, for both $\psi(3686)$ and $\psi(3770)$ we find that the partial decay width vanishes for a particular D meson mass shift of about 200 to 250 MeV, due to cancellations in the matrix elements caused by the nodal structure of the quark wave functions. For a mass shift of this size, the increase in phase space, would give $\Gamma^{\star}_{D\bar{D}}(\psi(3770)) \sim 1.2$ GeV for a constant matrix element. The enhanced widths of the $\psi(3686)$ and $\psi(3770)$ may be observable in the spectrum of dileptons produced in heavy ion reactions. As can be seen in fig. 2, the partial width for decay into the $D\bar{D}$ channel first increases to about 90 MeV and then drops to zero for a D meson mass shift of about 200 MeV.

In matter the total width of charmonium states is further enhanced by reactions with the surrounding particles, like e.g. $\psi + N \to \Lambda_c + \bar{D}$. The threshold for this process is fairly low; it is energetically allowed for charmonium masses $m_\psi \gtrsim 3.2$ GeV. The cross section, computed in the quark exchange model, is given in ref. [24]. For the $\psi(3686)$ the asymptotic value was found to be $\sigma_{abs}(\psi(3686) + N) \sim 6$ mb. The relatively small cross section is related to the compact size of the charmonium states. The contribution of this reaction to the in-medium width of the $\psi(3686)$ is, to lowest order in density, given by

$$\Gamma_N = \frac{1}{\tau} = \langle \sigma_{abs}(\psi(3686) + N) v_{rel} \rho_n \rangle, \tag{20}$$

where ρ_n is the density of nucleons in nuclear matter and v_{rel} is the average relative velocity in the initial state. Assuming that the ψ has a relative momentum p_ψ with respect to the rest frame of the medium , $v_{rel} = \frac{3}{4}\frac{p_F}{m_N}[1+\frac{2}{3}(\frac{m_N p_\psi}{m_\psi p_F})^2]$, where p_F is the Fermi momentum of nuclear matter. When $p_\psi = 0$, this gives the additional width $\Gamma_N \sim 4$ MeV at $\rho_n = \rho_0 = 0.17\text{fm}^{-3}$ and $\Gamma_N \sim 25$ MeV at $\rho_n = 4 \times \rho_0$. Even for $p_\psi = 1$ GeV$/c$, we find an additional width of only $\Gamma_N \sim 6.9$ MeV at $\rho_n = \rho_0$ and $\Gamma_N \sim 34$ MeV at $\rho_n = 4 \times \rho_0$.

Although there are no calculations of the corresponding reaction for the $\psi(3770)$, one expects a cross section of the same magnitude because the root-mean-square radii of the two charmonium states are similar [21]. In QCD [25,26], the leading order result for σ_{abs} is proportional to $\langle r^2 \rangle$. Therefore, the additional width of the charmonium states $\psi(3686)$ and $\psi(3770)$ due to scattering off the nuclear medium is expected to be small. Thus, we conclude that the total width of these resonances in nuclear matter is dominated by the decay into $D\bar{D}$ mesons. The small scattering contribution may play a significant role only at those densities, where the $D\bar{D}$ channel is quenched due to the nodal structure of the wave function.

For the $\chi(3556)$ a somewhat different picture emerges. We find that its width increases monotonically as the D meson mass decreases. In hadronic collisions [19] a large fraction of the J/ψ's stem from the radiative decay of χ's. If the $D\bar{D}$ width of the $\chi(3556)$ increases in matter, the probability for the decay into $J/\psi\gamma$ decreases. Thus, part of the suppression of J/ψ's in heavy-ion collisions may be due to this effect. The increase in the width of the $\chi(3556)$ could be observed by measuring the $J/\psi\gamma$ decay [19] in future heavy ion experiments [9].

In addition to the medium effects due to the partial restoration of chiral symmetry, one also expects mass changes due to modifications of the confining potential in nuclear matter. In our model, this effect will be reflected in a density dependence of the oscillator parameters β and δ, which parameterize the strength of the harmonic oscillator potential. A rough estimate of the expected change in δ at nuclear matter density, can be obtained by relating the expected mass shift of the J/ψ to a change in the confining potential. We use the relation $\delta m_{J/\psi} = \frac{3}{2}\frac{1}{M}\delta p^2$, which applies to the harmonic oscillator model. All model calculations [11–16] yield $\delta m_{J/\psi} \sim$ -7 MeV at nuclear matter density. This translates into $\delta\beta = -5.6$MeV, which can be safely neglected, since it corresponds to a relative shift in β of less than 2 % (see eq. (18)) and an even smaller change in the final result in fig. 2.

We conclude that measurements of the in-medium properties of charmonium states can provide valuable information on the characteristics of QCD in dense and hot matter.

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